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Generation Portfolio Analysis for a Carbon Constrained and Uncertain Future

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***Abstract*— Many modern electricity systems are faced with the challenge of reducing green house gas emissions and dealing with increasing and more volatile fuel prices. Adequately dealing with these issues requires the evolution of suitable generation portfolios. However, doubts remain if the liberalized marketplace will deliver such portfolios. Analysis is undertaken to try and determine how the generation portfolio on the all-Ireland system may evolve by 2020. Resulting portfolios are examined with respect to the impact of carbon costs on the development of the portfolio and in particular wind energy. An assessment is made of the exposure of the portfolios to fuel price volatility and how portfolios may wish to diversify to avoid this. The analysis endeavors to gain insight into the future generation portfolios with the aim of informing how policy instruments may be tailored to address these issues.**

***Index Terms*— Energy resources, environmental factors, fuel diversity, generation planning, power system economics.**

I. Introduction

Modern electricity systems are faced with many challenges such as pressure to reduce greenhouse gas emissions and increasing fuel prices and fuel price volatility. In the past such issues could have been considered in central generation resource planning in an attempt to best meet the future needs of consumers, the economy and society [1]. With the recent onset of market liberalisation in many systems, there has been a corresponding de-emphasis on central planning and it remains unclear if market forces will deliver suitable generation portfolios to deal with such issues [2].

Wind generation is seen in many countries as an important means to reduce greenhouse gas emissions [3]. However, the characteristics of wind generation differ from that of conventional generation and doubts remain whether the features of wind generation are reflected properly in electricity markets that were designed to suit conventional generation.

As the proportion of gas fired generation increases in many systems concerns grow about the over reliance on gas, which can exhibit volatile price patterns. This is of even more concern in systems which import a large proportion of their fossil fuel needs and it has been suggested that in many liberalised markets there is little incentive for investors or utilities to diversify generation resources [4],[5].

These issues pose a serious challenge to policy makers in many systems including the all-Ireland system. Responding to these issues in the current environment maybe more challenging than it has been in the past, as it must, in general, be done in parallel with an electricity market. A combination of market design features, direct or indirect subsidies, or even new state-owned generation may be necessary to fully address these issues. However, initiating the correct regulatory interventions or policies cannot be done without analysis and insight into how a system evolves into the future.

This paper endeavors to gain insight into possible generation portfolios on the all-Ireland system in 2020 with an aim to informing how policy may be tailored to address the issues mentioned above. The all-Ireland system has an installed capacity of approximately 8000 MW and is currently in the process of introducing a new electricity market [6]. The all-Ireland system is currently struggling with its emissions targets [7] and has an increasing dependence on gas fired generation. Ireland also has one of the best wind resources in the world. This paper uses a methodology developed in [8] and [9] to determine least cost-generation portfolios for various scenarios in 2020. Issues of load duration, plant utilization and system capacity are dealt with in the analysis and the unique characteristics of wind generation are also accounted for. The resulting portfolios can be viewed as what may result from a liberalized market if no intervention takes place and are assessed with respect to the issues highlighted above.

Section II gives a brief outline of the generation options and the least-cost portfolio optimization algorithm. Analysis in Section III aims to gain insight into the impact of carbon costs, the role of wind generation, and its effects on the generation portfolios. Section IV focuses on analyzing portfolios with insufficient generation diversity and exposure to fuel price volatility and investigates possible responses. Conclusions are given in Section V.

II. Generation Options and Portfolio Optimization

Least-cost portfolio analysis was undertaken for the all-Ireland system in 2020. It was assumed that, of the current generation capacity, only 800 MW of interconnection and 509 MW of hydro generation remain in 2020. It is assumed that there is a maximum of 3800 MW of usable wind generation resource,

This work has been conducted in the Electricity Research Centre, University College Dublin, Ireland, which is supported by Electricity Supply Board (ESB), ESB National Grid, Commission for Energy Regulation, Cylon, Airtricity and Enterprise Ireland.

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TABLE I
GENERATION COSTS AND CHARACTERISTICS

Plant Type	Notional Size of Installation (MW)	Plant Life (Years)	Build Time (Years)	Average Efficiency (%)	Capital Cost (€/MW)	Op & Main (€/MW p.a.)	CO_2 Emissions (Tons CO_2/MWh)	Availability (%)	Resource Limited (MW)
Coal PF	1000 (3 x 333 MW)	30	4	37	1,479,200	34,800	0.92	84	-
Coal IGCC	800 (2 x 400 MW)	25	5	48	1,761,321	69,000	0.71	84	-
Peat FB	150	25	4	37	1,223,807	55,200	1.15	87	1000
OCGT	110	20	1	43	518,411	36,000	0.47	92	-
CCGT	390	20	2	56	537,500	50,000	0.36	88	-
Wind 1 (On-Shore)	30 (15 x 2 MW)	20	2	-	981,475	34,800	0.00	-	1200
Wind 2 (Mix)	30 (15 x 2 MW)	20	2	-	1,028,775	54,250	0.00	-	2600
Biomass & Biogas 1	10	20	2	-	2,418,750	80,000	0.00	78	70
Biomass & Biogas 2	10	20	2	-	3,386,250	90,000	0.00	78	50
Biomass & Biogas 3	10	20	2	-	4,353,750	90,000	0.00	78	500

PF = Pulverised Fuel. IGCC = Integrated Gasification Combined Cycle. FB = Fluidised Bed.
CCGT = Combined Cycle Gas Turbine. OCGT = Open Cycle Gas Turbine.

enough to serve 22% of electricity demand. Further details of the least-cost portfolio analysis can be found in [8] and [9].

A. Generator Inputs

An extensive list of generator data was gathered for this work. Unit sizes, characteristics, efficiencies and costs were gathered from several sources [10]-[12]. Table I shows the generators, costs efficiencies and characteristics assumed achievable in the all-Ireland system by 2020.

B. Fuel Prices

Two fuel price scenarios are used in this work, a low fuel price scenario which is based on 2005 fuel prices and a high fuel price scenario based on projected 2020 fuel prices. See Table II. The fuel price scenarios were compiled from several sources [10]-[13]. The most notable feature in the high fuel price scenario, compared to the low is the relatively higher price of gas with respect to the other fuels.

TABLE II
FUEL PRICE SCENARIOS

Fuel	Low €/GJ	High €/GJ
Gas	4.31	5.54
Coal	1.59	1.65
Peat	2.64	3.12

C. Generation Adequacy

It is essential that each power system have enough capacity to serve the load to the extent defined by a system reliability criterion. Intermittent, non-dispatchable sources of generation, like wind generation, make a different contribution to the generation adequacy of a system than conventional dispatchable generation. Capacity credit studies [8],[9] were undertaken for each generation type to ensure each portfolio has sufficient capacity to meet a Loss of Load Expectation, LOLE, of 8 hours per year [14]. Fig. 1 shows the capacity credit of wind generation as a function of the installed wind capacity.

D. Least-Cost Portfolio Optimisation

A linear programming portfolio optimization algorithm [8],[9] is used to find the mix of generation technologies that, for a given set of inputs, results in the load being met at least-cost. Issues of plant utilization, load duration and generation adequacy are included in the analysis. However, temporal system aspects and unit start-up factors are not included. The algorithm optimizes the installed capacity of each type of generation in the portfolio and optimizes how they are utilized with respect to the load duration curve. The resulting portfolios are presented and analyzed in the following sections.

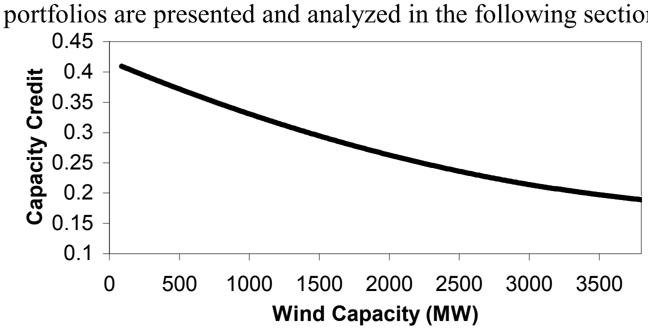


Fig.1. Capacity credit of wind generation.

III. CARBON COSTS AND THE ROLE OF WIND GENERATION

A. Least-Cost Generation Portfolio Results

Least-cost portfolios for the all-Ireland in 2020 system were examined for various fuel price and carbon cost scenarios to gain insight into desirable generation portfolios. Table III and Table IV shows the installed capacities of the least-cost portfolios. The cost of carbon in the all-Ireland system may be based on the European traded cost of carbon and may also include an additional factor reflecting the penalties incurred by not meeting international emissions targets. The cost of carbon is included here in the form of a carbon tax. If regulatory bodies can ensure that the cost of carbon is properly reflected in the marketplace, it is reasonable to assume, given the inputs, that these are the sort of generation portfolios that the industry will be heading towards in the year 2020.

TABLE III
PORTFOLIOS WITH INCREASING CARBON TAX FOR LOW FUEL PRICES

Plant Type	Installed Capacity (MW)					
	0 €/Ton CO_2	10 €/Ton CO_2	20 €/Ton CO_2	30 €/Ton CO_2	40 €/Ton CO_2	50 €/Ton CO_2
Coal PF	7060	0	0	0	0	0
Coal IGCC	0	0	0	0	0	0
Peat FB	0	0	0	0	0	0
OCGT	1732	2278	2572	2156	2469	2405
CCGT	0	6289	5826	6241	5805	5782
Wind 1 & 2	0	600	1200	1200	1800	2400
Biomass 1,2 &3	0	0	0	0	0	0
Interconnection	800	800	800	800	800	800
Hydro	509	509	509	509	509	509
Total	10101	10476	10907	10906	11383	11896

TABLE IV
PORTFOLIOS WITH INCREASING CARBON TAX FOR HIGH FUEL PRICES

Plant Type	Installed Capacity (MW)					
	0 €/Ton CO_2	10 €/Ton CO_2	20 €/Ton CO_2	30 €/Ton CO_2	40 €/Ton CO_2	50 €/Ton CO_2
Coal PF	7060	6560	5229	0	0	0
Coal IGCC	0	0	0	0	0	0
Peat FB	0	0	0	0	0	0
OCGT	1732	1838	2469	2381	2374	2374
CCGT	0	0	576	5765	5700	5630
Wind 1 & 2	0	1200	1800	2800	3800	3800
Biomass 1,2 &3	0	0	0	0	0	70
Interconnection	800	800	800	800	800	800
Hydro	509	509	509	509	509	509
Total	10101	10907	11383	12255	13183	13183

It can be seen that a CCGT based system is found to be least-cost once the carbon tax is 10 €/Ton of CO_2 and above for the low fuel price scenario and 30 €/Ton of CO_2 and above for the high duel price scenario. This is consistent with the industry in Ireland at present where most proposed generation projects are for the development of new CCGTs. It can also be seen that the optimal penetration of wind power increases as expected with increasing carbon tax. The increased gas price in the high fuel price scenario accelerates the role of wind as a means to reducing carbon emissions in a least-cost manner.

B. Emissions

Under the Kyoto Protocol, the Republic of Ireland must limit its increase in greenhouse gas emissions to 13% above 1990 levels in the period 2008-2012. In 2003, greenhouse gas emissions in Ireland were 25% above 1990 levels [7]. It can be seen from Tables III and IV that properly reflecting the cost of carbon in the marketplace is important to give a signal as to the appropriateness of coal based generation. This factor has a large impact on emissions. Given the long life span of generation plant, inappropriate coal plant operating during periods of high carbon cost may cause significant and unnecessary cost to the system and wider economy. Fig. 2 below shows the effect of the various carbon taxes on the emissions from the generation portfolios. This is expressed as a percentage of the scenarios with no carbon tax.

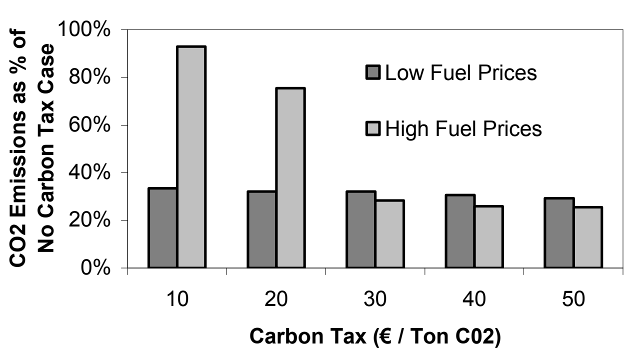


Fig. 2. Emission from portfolios for various carbon taxes and fuel price scenarios.

Even in a gas based system, the presences of a carbon tax plays an important role with respect to emissions by signaling the appropriate penetration of wind generation. For the all-Ireland system in 2020 it was found that 3800 MW of wind generation could result in a reduction in CO_2 of 21% from a purely gas based system.

C. Role of Wind Generation in Portfolios

An examination of the role of wind generation in least-cost portfolios was undertaken for a large range of gas price and carbon tax scenarios. These two variables have a large impact on the generation portfolios and have a significant uncertainty associated with them. It can be seen from Fig. 3 that wind generation plays a significant role in least-cost portfolios for a large range of scenarios. It can also be seen that for a considerable number of scenarios the optimal wind capacity was found to be the maximum amount assumed available, 3800 MW.

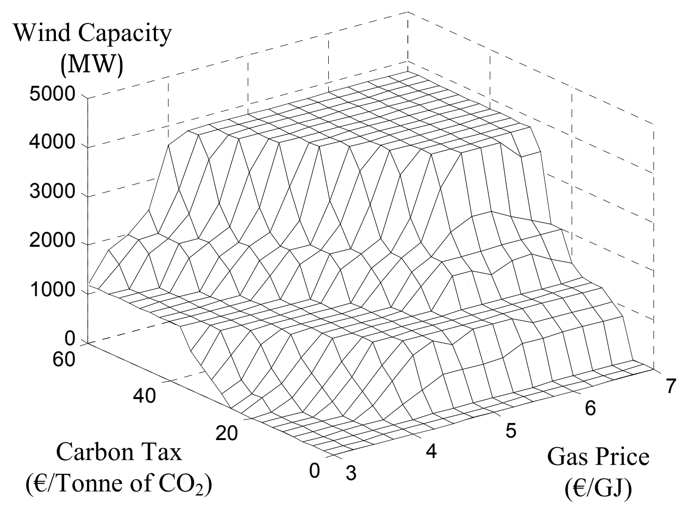


Fig. 3. Wind capacity in least-cost portfolio for various carbon tax and gas price.

The Republic of Ireland currently aims to serve 13.2 % of electricity from renewable sources by 2010 [15]. The analysis here assumes that there are no regulatory or market factors obstructing the development of wind generation and that the cost of carbon is fully reflected in that marketplace. This approach would be correct macro-economic practice but is currently not the case in the all-Ireland system. The results show that under these conditions there would be a significant development of renewable energy for many of the future scenarios. This approach would help towards meeting renewable energy targets perhaps without the need for additional subsidy.

D. Effect of Increasing Wind Capacity

Analysis was carried out to examine the effect of increasing wind capacity on the mix of remaining generation in the least-cost portfolios. Fig. 4 shows the installed capacities of the generation in the least-cost portfolios with increasing wind generation for the low fuel price scenario with no carbon tax. It can be seen that the increasing wind capacity causes a decrease in the amount of base loaded plant and an increase in the amount of peaking capacity required in least cost portfolios. This is due to the change that wind generation causes to the net-load duration curve. Similar trends were found for portfolios which had CCGTs as the base loaded plant. This behavior is in contrast to the impact wind capacity has on an existing portfolios where it normally displaces the units with higher incremental costs. To ensure efficient generation portfolios as wind capacity increases it becomes more important that the correct signals for reserve, mid-load plant and peaking plant are provided in the marketplace in the long-term.

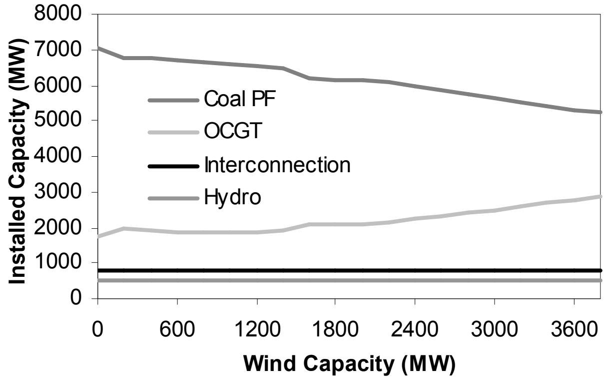


Fig. 4. Installed capacities of generation in least-cost portfolios against wind capacity for the low fuel price, no carbon tax scenario.

IV. Uncertainty and Portfolio Diversification

A. Background

The all-Ireland system relies heavily on imported fuel for electricity production. In 2003, in the Republic of Ireland, 88% of electricity produced was from imported fuels [16]. This means that Ireland may be exposed to price hikes and even possible shortages in supply as a result of economic and political changes in other countries. Assessing the detrimental effects that such events may have on the economy of the island is a difficult task and an important factor may be the level of exposure of competing economies to similar events.

The results given in Section III and analysis of the industry in Ireland at present suggest that it is very likely that gas fuelled plant will become the dominant means of electricity production in the future. Analysis carried out in [4] suggested that in 2001, in the Republic of Ireland, gas consumption accounted for 0.38% of GNP. By 2010 this figure may rise significantly. If gas were supplying 80% of electricity needs at the high fuel price scenario given in Section II, then gas consumption may account for up to 1.01% of GNP. A significant gas price shock at this stage would result in significant cost to the economy and a loss of competitiveness with respect to economies with lower gas price exposure. It is generally accepted that diversification of fuel resources will serve to reduce the exposure such risk.

B. Diversity

Correctly quantifying how much to diversify generation resources and determining what to diversify with is a challenging problem faced by policy makers. There is little agreement on the best approach on which to base generation diversification with the large amounts of unquantifiable uncertainty about the future proving conceptually challenging. However, two approaches have emerged as being possibly suitable.

In [17] the authors adopt the approach of mean variance portfolio theory to create generation portfolios, which can be analyzed on a risk return basis. This approach requires probabilistic quantification of the uncertainty of various factors. The analysis includes fuel price risk, and the authors derive a cross correlation matrix for the price of electricity generated from the various fuel types.

Sterling, [18] argues that mean-variance portfolio theory is not appropriate for dealing with exposure to fuel price fluctuations, as they have no pattern. The author states that diversification is a response to ignorance rather than quantifiable risk and suggests diversity should be quantified by using the Shannon-Wiener index. The author seeks diversity as a goal in itself rather than as a means of to reduce something specific.

Each approach has its strengths and weaknesses [5]. In this section both approaches are examined in the context of the all-Ireland system in 2020.

1) Mean-Variance Portfolio Theory

This approach requires the mean and standard deviation of the cost of electricity produced by the various fuel types. These were derived from historic fuel prices and it was found that electricity produced from gas and coal plant had a standard deviation of 8 €/MWh and 4.2 €/MWh respectively over the time period considered. The correlation coefficient was found to be 0.3. It is assumed that the standard deviation is zero for the cost of electricity produced from peat, biomass and wind generation. These values and assumptions are in line with the literature [2],[4],[17].

2) The Shannon-Wiener Index

The Shannon-Wiener index is mainly used in ecology as a measure of diversity. In [18] it is suggested that the index is also suitable for examining diversity in generation portfolios, as it does not require any "pretence to knowledge" over the future in terms of probabilistic measures. The Shannon-Wiener index H is defined as in (1) where p_n is the proportion of generation represented by the generation type n.

$$H = \sum_{i=N}^{N} -p_n \ln(p_n) \qquad (1)$$

With just one generation type the index has the value of zero. With two equal generation elements it has a value of 0.69, this rises to 1.1 with 3 equal elements and rises above 2 with 7 equal elements.

C. All-Ireland Portfolio Illustration

Both approaches to assessing the diversity or exposure to risk of the generation portfolio were applied to the All-Ireland system in 2020 for the high fuel price scenario and the 30 €/Ton of CO_2 carbon tax. The least-cost portfolio optimization was run for a wide range of portfolio options in order to search the space. Fig 5 and Fig. 6 show the results of the analysis. They plot the cost of electricity of the generation from a particular portfolio versus the standard deviation of the electricity cost and the Shannon-Wiener index. The x-axis of Fig. 6 has been reversed for ease of comparison. Table V shows the make up of the portfolios shown in Fig. 5 and Fig. 6. Also shown is the standard deviation of the electricity cost and the Shannon-Wiener Index for the current all-Ireland generation portfolio and the efficient frontiers. An efficient frontier is the frontier at which the price cannot be reduced any further without accepting an increase in the volatility or a decrease in diversity. In reality desirable portfolios should be at or near the efficient frontiers.

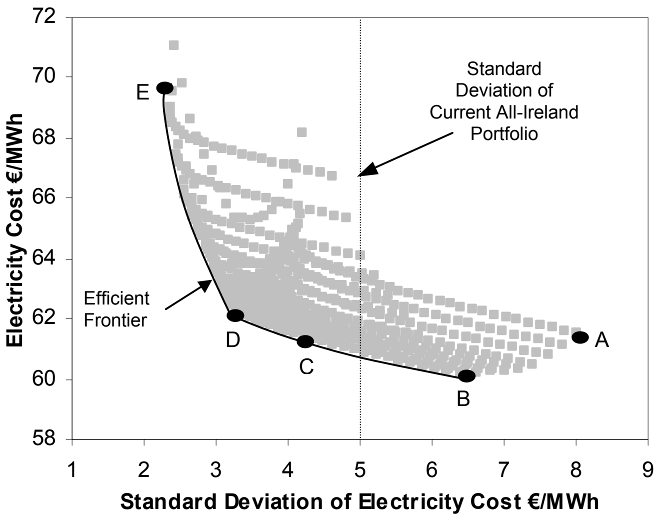


Fig. 5. Mean-variance portfolio analysis.

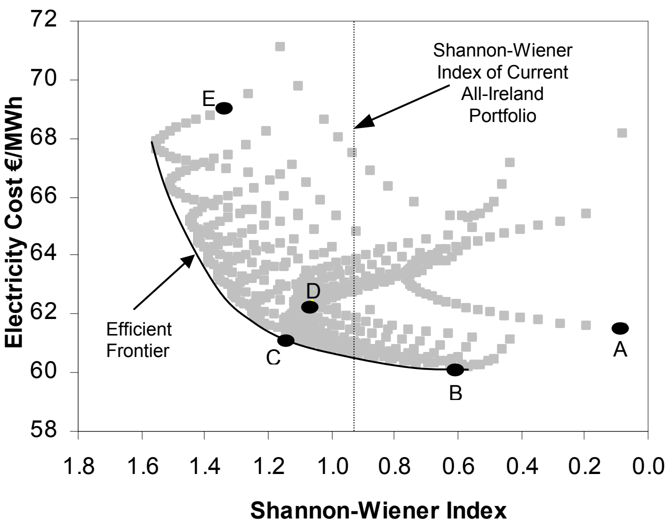


Fig. 6. Shannon-Wiener index portfolio analysis.

TABLE V
DIVERSITY ANALYSIS - SIGNIFICANT PORTFOLIO

Plant Type	Installed Capacity for Portfolio (MW)				
	A	B	C	D	E
Coal PF	0	0	0	0	0
Coal IGCC	0	0	2307	4180	3506
Peat FB	0	0	0	0	1000
OCGT	2013	2381	2374	2374	2374
CCGT	6778	5765	3394	1451	721
Wind 1 & 2	0	2800	3800	3800	3800
Biomass 1,2 &3	0	0	0	70	474
Interconnection	800	800	800	800	800
Hydro	509	509	509	509	509
Total	10100	12255	13184	13184	13184

What can be noticed from the application of both techniques to the all-Ireland system is that although the methods are conceptually different at a high level when they are applied to a scenario with limited options they results in similar outcomes. The main difference between the two techniques it that the mean-variance portfolio technique is less favorable towards gas-based generation as the inputs suggest that gas-based generation is more likely to be problematic.

In general a cost reflective market should result in electricity being served at least-cost. For this scenario this would correspond to portfolio B and would result in a relatively low level of fuel diversity and possible high levels of exposure to gas price spikes. If regulatory bodies do not ensure the cost of carbon is reflected in the marketplace then this may result in less wind generation causing less diversity and heavier reliance on gas, i.e. portfolio A. In both cases the generation portfolio is heavily reliant on generation from gas and considerably less diverse than the current all-Ireland generation portfolio.

It can be seen that portfolios that are more diverse than the current portfolio are achievable and may not necessarily come at a significant increase in cost relative to the least-cost portfolio. Portfolios C and D include some IGCC coal plant which decrease the reliance on gas, and which only slightly increase the cost of electricity. (IGCC plant were found to be more economic than PF plant due to the high carbon tax). Portfolio C, which lies on the efficiency frontier in both sets of analysis looks appropriate for this scenario. In this portfolio gas plant and coal each plant serve about 32% of the energy demand, while wind serves 22% and interconnection and hydro serve about 14%.

D. Ensuring Diversity in Generation Portfolios

Analysis in [4] and [5] and suggests that, in systems where gas generation is generally setting the market price, utilities are unlikely to invest in non-least-cost technologies for the sake of diversity. Given this and the current observable trends in the industry, it is difficult to envisage how the future all-Ireland generation portfolios will maintain adequate diversity in the liberalized marketplace unless there is some sort of targeted intervention. However, what form this intervention should take remains unclear. Direct state subsidies to specific industries have occurred in the past but may no longer be appropriate and may undermine the establishment of a fully liberalized marketplace. One approach may be to develop a market instrument that would provide an incentive to diversify, possibly based on one of the metrics used in the analysis here. Assessing how much diversity is appropriate or assessing the economic value of increased diversity is a challenging problem. Such an instrument would also have to be consistent and systematic as to provide the correct long-term signals for investment. The new market structure in the all-Ireland system includes a capacity payment mechanism [6], which could be thought of as catering for elements of "public good" or elements which may be insufficiently dealt with in the market. An option may be to deal with the portfolio diversity issue within this mechanism by somehow weighting payments with respect to diversity.

V. Conclusions

This paper presented high-level analysis of how the generation portfolio on the all-Ireland system may evolve by 2020. Portfolios were assessed in relation to the issues surrounding the reduction of CO_2 emissions and the exposure of fuel price shocks.

Analysis suggested that fully reflecting the cost of carbon in the marketplace was important in terms of signaling for the appropriate generation capacity in the long term. It is suggested that the integration of wind energy is the main route to increasing renewable energy and decreasing emissions in the all-Ireland system. Reflecting the cost of carbon in the marketplace is important for wind generation but it is essential other issues are also addressed. Markets, which have been designed to suit conventional generation, may place unnecessary obstacles to the development of wind generation and it is important that these obstacles are removed. Results here showed that wind generation also causes a change in the makeup of the remaining generation in the least-cost portfolio. With wind generation it becomes more important that the correct long-term signals for reserve, mid-load plant and peaking plant are provided in the marketplace.

Two methods of assessing generation diversity were applied here to the all-Ireland system in 2020. Despite being conceptually different approaches, the outcomes, in a system with limited options, were quite similar. It appears that direct intervention will be necessary in the all-Ireland system to ensure that the system does not become over dependant on gas fired generation. It may be desirable to design a market instrument to provide an incentive for diversity. However, valuing diversity and designing the appropriate mechanism will be a challenging task.

To some extent various market instruments, such as carbon taxes and diversity inducements, may provide participants with conflicting incentives [2]. This however, reflects the competing priorities of policy makers facing multiple objectives. Providing there is just one clear, well-designed instrument reflecting each objective then the marketplace should deliver the least-cost solution to the specified objectives.

VI. Acknowledgements

The authors gratefully acknowledge Garth Bryans, Morgan Bazilian of SEI and John Fitz Gerald and Niamh Mc Carthy of the ESRI for their help during this work.

VII. References

[1] H. Khatib, *Economic Evaluation of Projects in the Electricity Supply Industry*, no. 44, IEE Power and Energy Series, 2003.

[2] Bergin, A., Fitz Gerald, J., Keeney, M., O'Malley, E. and Scott, S., 2005, "Aspects of Irish Energy Policy," 2005, [Online]. Available: http://www.esri.ie

[3] K. Neuhoff, "Large-scale deployment of renewables for electricity generation," *Oxford Review of Economic Policy*, Vol. 21. pp. 88-110, 2005.

[4] J. Fitz Gerld, "The Macro-Economic Implications of Gas Dependence," 2002, [Online]. Available: http://www.esri.ie

[5] F. Roques, D. Newbery, W. Nuttall, S. Connors and R. de Neufville, "The diversification value of nuclear power as part of a utility technology mix when gas and carbon prices are uncertain," *in Proceedings IAEE European Energy Conference*, Bergen, Aug. 2005.

[6] All Ireland Project, "Single Electricity Market (SEM) High Level Design Decision," 2005, [Online]. Available: http://www.allislandproject.org

[7] Energy Policy Statistical Support Unit of Sustainable Energy Ireland, "Energy in Ireland 1990 - 2003: Trends,Issues and Indicators," 2005, [Online]. Available: www.sei.ie

[8] R. Doherty, H. Outhred and M. O'Malley, "Establishing the role that wind generation may have in future generation portfolios," *IEEE Trans. Power Systems*, (*in review*), 2005.

[9] R. Doherty, "New Methods for Planning and Operating Modern Electricity Systems with Significant Wind Generation, " Ph.D. Thesis, University College Dublin, 2005.

[10] Royal Academy of Engineering, "The Costs of Generating Electricity," 2004, [Online]. Available: www.raeng.org.uk

[11] ESB National Grid, "Impact of Wind Power Generation in Ireland on the Operation of Conventional Plant and the Economic Implications," 2004, [Online]. Available: http://www.eirgrid.com

[12] Commission for Energy Regulation, "Best New Entrant Price 2005, " 2004, [Online]. Available: http://www.cer.ie

[13] European Commission Directorate-General for Energy and Transport, "European Energy and Transport – Trends to 2030," 2003, [Online]. Available: http://europa.eu.int

[14] ESB National Grid, "Generation Adequacy Report 2004-2010," 2003, [Online]. Available: http://www.eirgrid.com

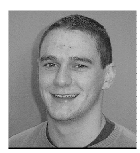
[15] European Union, "Directive 2001/77/EC of the European Parliament and the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market," 2001, [Online]. Available: http://europa.eu.int/

[16] International Energy Agency, "Energy Policies of IEA Countries – Ireland 2003 Review," 2003, [Online]. Available: http://www.iea.org

[17] S. Awerbuch and M. Berger, "Applying Portfolio Theory To EU electricity Planning And Policy-Making," Feb. 2003, [Online]. Available: http://www.iea.org

[18] A. Sterling, "Diversity and ignorance in electricity supply investment," *Energy Policy*, vol. 22, pp. 195-216, Mar. 1994.

VIII. Biographies



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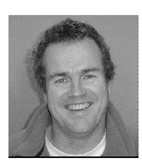

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